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Dr. Nina Yurchenko

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R&DCFM, National Academy of Sciences
8/4 Zheliabov St.
Kiev 252057
Ukraine

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This report results from a contract tasking R&DCFM, National Academy of Sciences as follows: The contractor will perform research which should support design of a new type of surface arrangement aimed to induce and maintain streamwise vortices to satisfy in a best way the requirements of optimal flow control (delay of separation/laminar-turbulent transition or enhancement of heat transfer) and at the same time to be technologically realizable and operationally convenient.



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# DEVELOPMENT OF BOUNDARY LAYER CONTROL TECHNIQUES EFFICIENT FOR FLOWS UNDER BODY FORCES

*Principal Investigator:* Dr. **N.F.Yurchenko**

***Research & Development Center of Fluid Mechanics (R&DCFM),***
***National Academy of Sciences of Ukraine***

*8/4 Zheliabov St., 252057 Kiev, UKRAINE*
*Tel: +38044 441-7452*
*Fax: +38044 216-0425*
*E-mail: yur@rdfm.freenet.kiev.ua*

## 1. INTRODUCTION

Practically important flows can be characterized as flows with available body forces which can account for a complex geometry of a body, flow-body temperature differences, gravitational or electromagnetic fields for some types of fluids. It means that to be efficient, the boundary-layer control techniques must be

- correlated with the specific features of the vortex dynamics of such flows;
- flexible, i.e. allowing the adjustment of control parameters to changing flow conditions or any other operation requirements;
- as simple as possible and reliable in design, operation and long-term exploitation;
- based on the advanced fundamental science involved to solve formulated problems and to use practical experience including successful results obtained due to numerous trial-and-error methods.

An essential feature of fluid motion under body forces is the natural development of counter-rotating streamwise vortices. It is known to be an inherent feature of a variety of flows but can be rigorously described for bounded flows affected by body forces. Being one of the fundamental boundary layer problems related to the laminar-turbulent transition and turbulence production, it is also a key point for applications dealt with the intelligent ways of flow control.

Therefore the **objective** of the present work is to propose an optimal flow-control technique based on inherent features of the vortex dynamics of boundary layers affected by body forces.

One of the typical and important applications of this research relates to the improvement of low-pressure turbine blade performance which is strongly influenced by unsteady flow separation and transition. It is connected with the specific conditions of a gas turbine engine operation from take-off to high altitude cruise causing significant variations of Reynolds number. Generally, the flow around a turbine blade can be specified as a turbulent flow affected by centrifugal forces and buoyancy. According to the mentioned above inherent feature of such flows, experiments [19, 30] displayed streamwise vortices naturally arising in a turbine blade boundary layer.
Therefore vortex dynamics of the flow around a turbine blade was considered as a prototype problem to study the vortical structure evolution in boundary layers under centrifugal forces and possibilities to effectively manipulate this structure.

The work consists of three matched parts:
(1) analysis of the data obtained using liquid crystal visualization around the turbine blade,
(2) experimental investigation of a boundary layer response to vortices specially generated over concave surfaces,
(3) numerical simulation of a transitional boundary layer with induced streamwise vortices.

As a result, an engineering method is developed and tested to generate a system of regular streamwise vortices with a given scale correlated with basic flow parameters to control momentum and heat fluxes in order that to change boundary-layer characteristics in a necessary way.

## 2. BACKGROUND

### 2.1. Vortex dynamics of boundary layers affected by body forces

The classical example of a boundary-layer flow under body (centrifugal) forces is formulated and extensively studied as the Goertler instability problem. Streamwise counter-rotating vortices were established to characterize the main type of instability of such flows.
The comprehensive review of studies related to the centrifugal case was given by W. Saric [37]; detailed and diverse original results on the Goertler problem are presented in [1, 8-11, 16-18, 20, 26, 27, 32, 37, 38, 40, 41, 44-46, 53]. Some practical aspects were considered in [26, 38, 49, 51, 52, 54, 55] where, in particular, a possibility of local heat transfer enhancement up to 360-400% depending on Prandtl number was reported [26].
On the one hand, the Goertler instability mechanism driving the development of streamwise vortices in boundary layers affected by centrifugal forces is well examined [4, 5, 9, 10, 26, 32, 38, 39, 40, 46-53, 55, 57, 60] and the problem was shown to be a suitable model for studies of similar eddy structures that exist in transitional and turbulent flat-plate boundary layers [9, 10, 40, 57, 60]. On the other hand, the longitudinal vortices, induced, maintained and controlled, give a convenient and effective means for the management with the flow integral characteristics, e.g. for favorable influence on skin friction, flow separation or heat transfer [26, 49, 51, 52, 54-56 22-25, 28, 36, 37].

Numerous theoretical models, numerical and experimental results made it possible to predict the dynamics and specific features of the vortical structure depending on the initial flow conditions. At this point, the stability problem closely comes up to the problem of receptivity connected with a flow response to disturbances penetrating or induced by any means in a boundary layer. These matched problems were analyzed with respect to streamwise vortices in [11, 27, 45, 46, 54, 56] that accordingly brings to the development of corresponding boundary layer control methods [54, 56].

However streamwise vortices are also an essential flow structural element in a general laminar-turbulent transition process over surfaces of different shape and curvature. Fluid motion in a form of the longitudinal vortical systems was found to be typical (or significant) for a wide range of various flows. For instance, streamwise counter-rotating vortices are known to develop naturally in flows with available body forces of different nature, such as

- flows in a gap between concentric cylinders (Taylor vortices);
- boundary layers over heated surfaces, i.e. bounded flows affected by buoyancy (both in natural and mixed convection cases);
- flows considered in MHD with transverse magnetic fields,
- secondary flows in curved channels and river-beds,
- Langmuir circulation in ocean upper layers.

In addition, the mentioned large-scale vortical motion was experimentally found in turbulent boundary layers affected by centrifugal forces [41], what immediately makes this structure more attractive as a potential basis for many applications. More generally, the role of coherent vortical structures in transport phenomena was investigated and recognized for laminar and transitional as well as for turbulent flow fields [9, 40, 58]. Coherent eddy structures existing in mixing layers, in near- and outer-wall regions of turbulent boundary layers provide means to control turbulence what was shown using an instability approach [57-60].

Unlike turbulent motion described in the frame of ensemble-averaged models, i.e. by averaging the Navier-Stokes equations, this regular fluid motion may suppose more deterministic approach to its description. For instance, in relation to coherent structures, it was made due to the stability analysis applied to the wall region of a turbulent boundary layer using normally compressed Blasius velocity profile close to the wall which smoothly merged with the mean turbulent velocity profile [57, 59].

Structural and vortex dynamic similarities give grounds to combine different flows into groups supposing similar mechanisms of their development and behavior [53]. As a result, it allowed to mathematically rigorously formulate a new theoretical approach [32, 33] alternative to the traditional stability analysis that gave a deeper insight into the mechanisms of the streamwise vortical structure formation. It was shown that all specific features of the boundary layer development under body forces (centrifugal, magnetic or buoyancy) compared to the known solutions for a flat plate case (for instance, Blasius boundary layer) must explicitly depend on a small parameter related to the value of these body forces ($\varepsilon = 1/Re_R$ in case of centrifugal forces, where $Re_R$ is a Reynolds number based on the curvature radius). Mathematically it means that the problem is singularly disturbed by this small parameter. Hence using the method of matched asymptotic solutions, the equation systems were obtained for corresponding expansions of an unknown solution valid for certain flow domains, as well as the space scales of these domains depending on the basic flow parameters. Physically these domains represent flow zones with essentially different dynamical structure and space characteristics which are the natural consequence of the flow development under body forces. Longitudinal vortices, as an essential flow-structure feature, were shown to originate from the interaction of two vorticity sources (due to viscous and centrifugal forces) when their intensities become comparable at a certain distance,

$$X_o = AR\, Re_R^{-1/3},$$

displaying a minimum space-scale of

$$L_o = R\, Re_R^{-2/3}.$$

Thus the universal physical mechanism of the vortex dynamics in boundary layers under body forces yielding the streamwise vortical structure as an inherent feature of such flows give grounds to focus the studies on

(i) mechanisms and possibilities to manipulate this structure screating favorable flow conditions for its formation with required parameters;

(ii) receptivity of boundary layers under body forces to regular longitudinal vortices as a basis for applications dealt with the control of flow integral characteristics (skin friction, flow separation or heat transfer) [50, 52, 54, 56, 58];

(iii) formulated problem in the frame of the well-developed case of boundary layers affected by centrifugal forces that gave suitable models for studies of similar eddy structures that exist in transitional and turbulent boundary layers [9, 58].

### 2.2. Boundary layer control based on surface modifications

There is known a class of boundary-layer control methods based on manipulations with the surface properties, e.g. using various types of roughness, riblets or compliant coatings. Initially, the idea for the development of such methods arose from the studies of skin structure of fast-swimming marine animals: sharks, sail-fish, dolphins (see, e.g. [2, 31]). These studies encouraged numerous modeling approaches [3-5, 47, 48] in fluid dynamics where the approaches themselves and parameters of the surface-layer properties were chosen mainly by the method of trial and error. However obvious benefit for drag reduction obtained both numerically, and experimentally, stimulated fundamental investigations as well as the recent development of more sophisticated approaches based on various types of actuators. Since the latter are usually more expensive and less reliable in practical operation than passive boundary-layer control methods, ribleted surfaces stay more advantageous for many applications, especially in aerodynamics.

For instance, it was shown that the application of riblets can stably give about 6-9% of a turbulent drag reduction depending on their space scales and geometry. This value was repeatedly obtained both in experimental, and numerical investigations of flows over flat plates, airfoils, bodies of revolution [9, 15, 21, 32, 42]. Besides, riblets are effective in a regime of a laminar-turbulent transition too (up to 13% drag reduction was reported [31]) where velocity fluctuations reach their peak values. It was conjectured that, in addition to hampering the momentum exchange in the very vicinity of the wall, the riblets can delay the development of initial turbulent structures in time and space.
In addition, recent publications [21] reported about a significant portion of a drag reduction over ribleted bodies of revolution also due to a reduced separation zone. The double effect of ribleted surfaces (turbulent drag reduction and separation control) can be used most efficiently for flows affected by body forces, such as flows past configurations with curved and/or heated surfaces. These flow conditions are typical for numerous technical flow devices and aerodynamic applications whose performance is strongly related to the flow quality.
In particular, the experiments were carried out by Maciewski and Rivir [29] where heat transfer was measured from a constant temperature surface with longitudinal riblets on a turbine blade vane. There was registered 4-8% heat transfer reduction both with and without free-stream turbulence. Using the Reynolds analogy, one can expect 2-4% reduction in skin friction.

Any means to favorably modify the body-flow interaction are therefore potentially of high technological interest. However, in order to be of practical engineering significance, flow control techniques are required to be simple, flexible and reliable realizations of the achieved research results.
The main limitations and disadvantages of surfaces with complicated configuration, including riblets, for the boundary-layer control purposes are the following.

- Pollution of a surface is an essential problem even for air applications of riblets which typically represent a thin polymer foil fixed to the rigid surface. It can (1) significantly change the configuration geometry, thus eliminating its favorable influence on a flow structure, i.e. an expected integral effect and (2) cause considerable difficulties dealt with a non-destructive surface cleaning.
- Increased "wetted" ribleted surface compared to the smooth one results in failures to obtain greater total drag reduction.
- Fixed parameters of riblets and their position on a body suppose a certain compromise between the requirement to increase the system efficiency for a selected critical flow regime and to make it least disadvantageous for other typical operating conditions.

Moreover, advanced requirements of new technologies to efficient boundary-layer control methods cannot be satisfied unless these methods are developed taking into account the optimization of the whole object where they are intended to be applied. The optimization of one system or function of a complex machine, as well as its tuning to one set of defining parameters, often contradicts other requirements dealing with the optimal operation of the machine. The ribleted surfaces, as well as other known passive boundary-layer control techniques, are usually developed and adjusted to certain critical regimes of the body motion while staying useless or even disadvantageous for other regimes. Besides, applied boundary-layer control methods are, as a rule, not evaluated from the acoustical side although low-noise requirements have nowadays no less significance than those to drag reduction or heat transfer enhancement. This weak point is especially typical and essential for any active techniques which use movable or oscillating elements as parts of a construction.

Therefore the optimal design of a real object should start from a clear formulation of a set of practically important parameters to be considered at any stage of the design. It will give a necessary basis for modeling which, on the one hand, must be supported by the fundamental scientific knowledge and, on the other hand, will result in concrete recommendations dealing with the application of the results.

Thus, ***efficient boundary layer control*** *means a combination of advantages given by a smooth surface with a possibility of its adjustable properties, e.g. in a form of riblets or ribs which are switched on at necessary moments/regimes of motion with the parameters best corresponding to the current flow conditions.*

In this connection, riblets or ribs are proposed to be modeled by inducing thermally-driven flow inhomogeneities in the boundary-layer flow. Electrically heated flush-mounted strips oriented in the streamwise direction and separated from each other by thermally insulated strips create a temperature gradient periodic in the spanwise direction, at the same time keeping the surface smooth. Thus constructing a surface temperature field, one can cause the development of a specially organized vortical structure in the boundary layer flow. The idea proved to work successfully to generate and control Tollmien-Schlichting waves [25]. In the present case,

streamwise vortices in the near-wall region of a boundary layer are generated to effectively influence momentum and heat fluxes changing the integral characteristics of the boundary layer.

Thus **the basic research efforts are focused on gaining an insight into the development and behavior of the vortical structure induced in a boundary layer under centrifugal forces by the organized temperature inhomogeneity of a smooth surface.** The formulated problem is in agreement with practice interests and requirements since the majority of engineering applications relates to flows over curved surfaces with a temperature different from that of the free-stream.

## 3. ANALYSIS OF THE FLOW STRUCTURE AROUND A TURBINE BLADE

Since one of the typical applications of the proposed and developed method of the optimal boundary-layer control under body forces deals with improvement of a turbine blade performance, the flow structure was analyzed over a low-pressure turbine blade. The initial results for the analysis were taken from the experiments carried out under the leadership of R. Rivir [29, 34].

Flow geometry and properties were determined by the blade shape and the main flow parameters:
for the pressure surface, the curvature radius changes from the leading edge ($R$=1/16"-1/4") through $R$~1" to the aft ($R$=12"); the cord Reynolds numbers is within $Re_C$=50,000-300,000, typically about 100,000. Liquid crystal visualization showed streamwise vortices, or a finger-type flow structure, with the space scale $\lambda_z$=0.8 mm naturally developing over the concave (pressure) side of the blade at $Re_C$=67500 in the range of $x_0/c\approx0.2$-0.7 (chord, $c$=7").

These experimental results were processed and analyzed using the theoretical estimates for minimal space scales of developing longitudinal vortices (see § 2.1 and [32]), as well as the Goertler stability analysis.

According to the theory [32], $\lambda_z=8L_0$ where $L_0 = R\, Re_R^{-2/3}$ is a vortex space scale normally to the velocity vector. Therefore the scales, $L_0$, of the streamwise vortical structure expressed in terms of the basic flow parameters were calculated and found to be $L_0$=0.1mm for $R$=5", $Re_C$=67,500; $L_0$=0.09 mm for $R$=5", $Re_C$=100,000; $L_0$=0.12 mm for $R$=10", $Re_C$=67,500, having shown a good agreement with the value of $\lambda_z$=0.8 mm observed experimentally in the boundary layer of a turbine blade..

The $x_0/c$ value, nondimensional downstream distance where the streamwise vortices may appear under given experimental conditions, was checked for 3 values of curvature radius, $R$=0.7", 5.0", 12.0", and $Re_C$ = 100,000 and 67500. It showed a good agreement between the results of an experiment ($x_0/c$=0.2) and calculations based on the theoretical formula $X_o = AR\, Re_R^{-1/3}$ and given flow parameters.

The Goertler theory was used to interpret the experimental data and to establish its correlation with the used above theoretical approach. The well-known centrifugal stability diagram is very demonstrative in relation to the amplification rates of streamwise vortices with various scales which evolve in boundary layers depending on the Goertler number $G = U_0\, \delta_2^{3/2}\, \nu^{1}\, R^{-1/2}$. Vortices described by the nondimensional wave length, $\Lambda = \lambda_z^{3/2}\, U_0 / \nu R^{1/2} \approx 39$, are neutral, i.e. have a zero amplification rate for a wide range of Goertler numbers. Larger scale vortices are described in the Goertler diagram by the straight lines of $\Lambda$ = const > 39. In this connection, it was interesting to check where the experimentally observed vortices can be found on the diagram. This estimation was made for the 8 mm scale vortices according to $\Lambda = \lambda_z^{3/2}\, Re_C / c\, R^{1/2}$:
for $R$=5", $Re_C$=67,500 it was found that $\Lambda = 24$;
for $R$=5", $Re_C$=100,000 -- $\Lambda = 36$.
It means that the streamwise vortical structure registrated in the boundary layer of a low pressure turbine blade is of a neutral type, i.e. neither amplifying, nor decaying in a downstream direction. This flow structural feature can be used to keep a necessary thermodynamic balance in a boundary layer due to one or another method of the boundary layer control. In the controlled case, it is essential to maintain the favorable vortical structure as long as possible. This mechanism can be well seen and exploited in the frame of the receptivity problem.

Thus the application of the two supplementing theories (asymptotic approach to flows affected by body forces and the classical Goertler instability approach) allowed to reveal physical mechanisms of the studied flow and to get dimensional values of the vortical structure space-scales correlated with the basic flow parameters. In particular, the implemented analysis confirmed the supposed nature of the observed regular flow structure

stipulated by the action of the centrifugal mechanism having shown the neutral type of naturally developing streamwise vortices..

Therefore initiating and maintaining a vortical structure with the scale and properties corresponding to requirements of the flow optimization one can provide a proper thermo-dynamical balance in a boundary layer, i.e. in practical terms, control the flow separation on a suction side of a turbine blade.

## 4. EXPERIMENTAL MODELING

The first part of the experiments aimed

1) to demonstrate an effect of specially induced z-periodic disturbances/longitudinal vortices on integral boundary-layer characteristics;
2) to investigate the boundary layer receptivity to the space-scale of induced vortices;
3) to give preliminary assessments for the numerical simulation.

### 4.1. Experimental facility and measurement techniquess

The main part of experiments was carried out in a low-turbulent water channel (free-stream turbulence level was typically less than 0.1%) with an open test section of 10 x 25 x 300 cm [46]. The studied boundary layer developed on its changeable bottom, 25 x 300 cm, which could be flat or contain a concave section (curvature radii, $R$ = 1.0, 4.0 and 12 m) starting at $x$=1m and having the same sag, $\Delta y$=5 cm, for all three curvature values. Such test-section configuration resulted in a slight varying streamwise gradient of a free-stream velocity over a concave part of the bottom. To avoid its effect, an equidistant top wall was used for the case of $R$=1 m. The free-stream velocity range, $U_0$=0.5-50.0 cm/s allowed to examine thoroughly the laminar-turbulent transition area up to developed turbulence.

The flow field was visualized using electro-chemical tellurium method [43, 46] which is similar to the well-known smoke-wire visualization technique in air. Together with the laser velocimetry (LDA), it gave information about the velocity distributions in a boundary layer. The test-plate arrangement and the measurement scheme are shown in Figure 1,a. The tellurium-probe, a cathode (a fine wire with the diameter of 0.05-0.18 mm) having been $z$-oriented, emitted sequences of colored **Te**-colloidal lines under periodically applied voltage pulses; the lines initially parallel to the wire-probe, deformed downstream according to $U(z)$ velocity distribution in the boundary layer as it is shown in the figure. Normally mounted **Te**-probes gave an idea about the normal velocity profiles, $U(y)$, which, in addition, were measured with the LDA system.

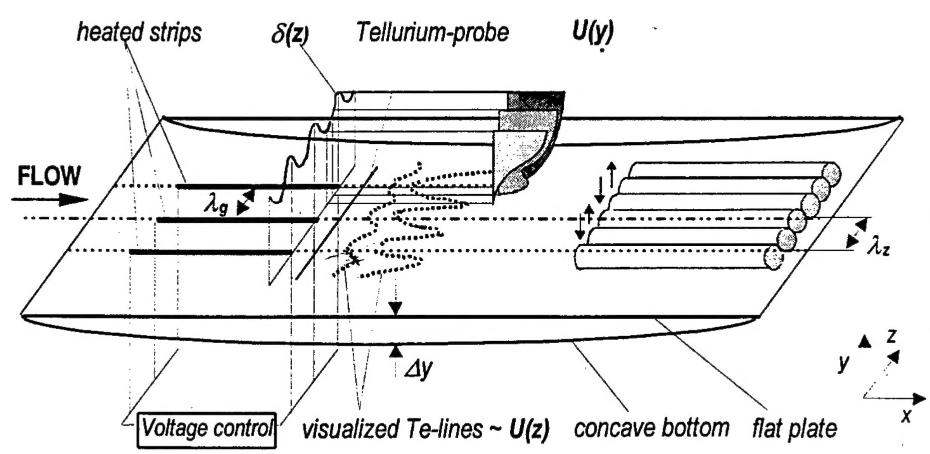



Figure 1,a. Water-channel test-plate and measurement schemes

The traversing mechanisms were used to choose a measurement section (to move **Te**-probes and the LDA optical blocks) along and normally to the test plate, the second one having had the displacement accuracy of about $10^{-5}$m. Different measurement sections in the *zx*-plane related to the longitudinal vortical system were chosen by moving the vortex-generator array in *z*-direction within the $\lambda_g$ distance. A typical triad of such $U(y)$ profiles characterizing the developing longitudinal vortical system was measured for *z*-values corresponding to low-speed (down-wash), high-speed (up-wash) regions and an intermediate position (near the vortex axis), the inflexion point having been found at the wall for the first profile and moved away from the wall for the third one.

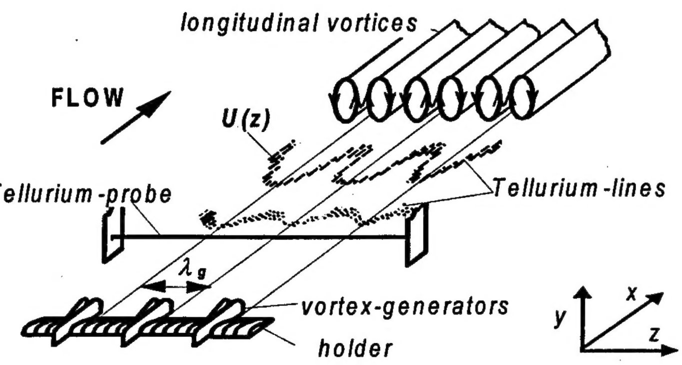



Figure 1, b. Generation of streamwise vortices using a vortex-generator array

Regular longitudinal vortices were induced using mechanical vortex-generators (Figure 1,b) and thermally driven longitudinal strips regularly spaced on the surface in *z*-direction at a $\lambda_g$ distance from each other (Figure 1,a). The vortex-generators were made from folded rectangular 0.5x1.0 cm pieces of thin Aluminum foil with rounded corners and split at their leading or trailing edges [46]. They were mounted vertically in a holder which was placed on the test surface along spanwise direction. The holder was fabricated as a bar of a segment-type cross-section with normal slots for vortex-generators, 2-mm distance between the slots, having provided the minimal scale of generated vortices $\lambda_g$=2 mm.
The thermal strips represented resistively heated flush-mounted wires. There were two sets of the strips of different length tested in the experiments: $L_1$=2 cm and $L_2$=20 cm. The first one was supposed to provide more concentrated effect on the flow as an initiating and scale-giving factor; the second one should influence in a distributed manner creating a constant boundary condition. In both cases, the "ribbed" section started at $X$=0.9 m from the virtual boundary layer beginning and two space-scales of the vortical system were examined which were determined by the distance between the neighboring strips, $\lambda_g$=1.2 cm and 2.4 cm. Depending on the basic flow parameters, streamwise vortices developed over the stripped section or downstream of the vortex-generator array with the scale equal to one initiated, $\lambda_g=\lambda_z$, or with a certain different scale supported by the flow, $\lambda_g\neq\lambda_z$. Typically, the experiments were conducted at the length-based Reynolds number $Re_x$=(0.6-1.0)x$10^5$; Tellurium visualization technique worked satisfactorily at the free-stream velocities $U_0\leq$0.1 m/s.

The Plexiglas test-plate provided both electrical, and thermal insulation of the heated strips to create a *z*-periodic temperature gradient on the surface and, consequently, the effect of a ribleted surface. Changing the applied voltage, one could vary the temperature gradient, thus realizing the control function: from $\Delta T$=0 (no special influence) to $\Delta T\approx$70°C.

### 4.2. Results and discussion

One of the laminar-turbulent transition stages is known to be characterized by the natural development of a streamwise vortical structure. However, it is very irregular in space and nonstationary in time what, in particular, strongly complicates its measurements and further interpretation of the results if a point-to-point measurement technique (like one-probe thermoanemometry or LDA) is used. Besides, many boundary-layer control applications require to maintain longitudinal vortices as long, as possible before their meandering stage and breakdown start. It can be reached due to the generation of a system of regular vortices.

Mechanical vortex-generators proved to be an effective engineering solution for the flow separation control but are operationally inconvenient or disadvantageous for many other problems. However, they are a perfect tool for laboratory studies giving regular and stable velocity distributions typical for a longitudinal vortical system. Figure 1 shows the examples of such "certified" distributions: wavy *U(z)* velocity profiles and a sequence of normal *U(y)* velocity profiles with a "floating" along *y* inflectional point. They can serve as an evidence of available streamwise vortices in the flow. Numerous experiments have shown that the mentioned *U(z)* velocity profiles give a sufficient evidence of embedded streamwise vortices in a boundary layer and are suitable to analyze their growth rate as well as a flow response to any external excitation. Therefore the experimental efforts and the analysis of the results are focused mainly on *U(z)* velocity distributions obtained under various conditions.

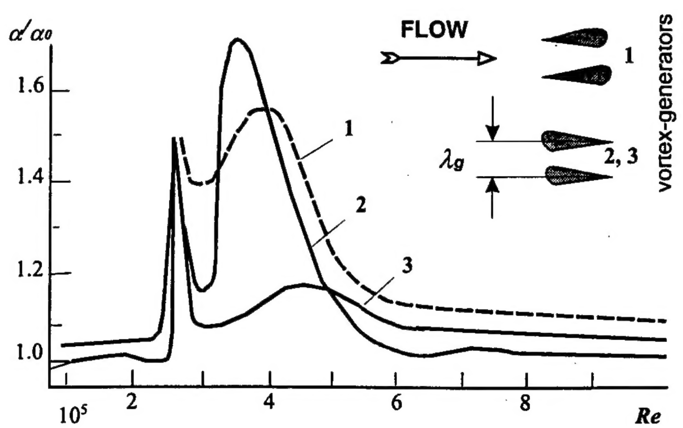



Figure 2,a. Relative growth of heat transfer coefficient $\alpha$ in a boundary layer downstream of the array of vortex-generators [54] with a sharp (1) and rounded leading edges (2,3): $\lambda_g$=1.5 cm (1, 2) and 1.8 cm (3)

Selective response of a boundary layer to the scale of generated vortices is demonstrated in Figs. 2 and 3, correspondingly in terms of integral characteristics and velocity field modifications downstream of the vortex-generator array.

Figure 2,a manifests the benefit of the induced longitudinal vortices for heat transfer enhancement dependent on the $\lambda_g$ scale. These measurements (as opposed to the rest of the experiments reported in the present work) were conducted in a wind-tunnel over a uniformly heated flat plate [54]. The first peak in $\alpha/\alpha_0(Re)$ at $Re \approx 2.6 \cdot 10^5$ is explained by the mere thermal conductivity of the vortex-generators placed directly on a tested Aluminum-foil surface having a temperature difference, $\Delta T$=20°C, with the mean flow.

Another practical advantage of embedded streamwise vortices is demonstrated in Figure 2,b in a form of the boundary layer separation control under the adverse pressure gradient in the flow along a concave section (it happened because of the mentioned "spoon-like" test-plate configuration shown in Figure 1,a). The top view of a visualized flow field shows the breakdown of Tellurium-lines immediately downstream of the rounded backward surface step at the concave section (a), while the vortex-generator array mounted on the surface (see a scheme in the top right corner) makes the flow pattern orderly with the space-scale of the vortical structure corresponding to the one induced.

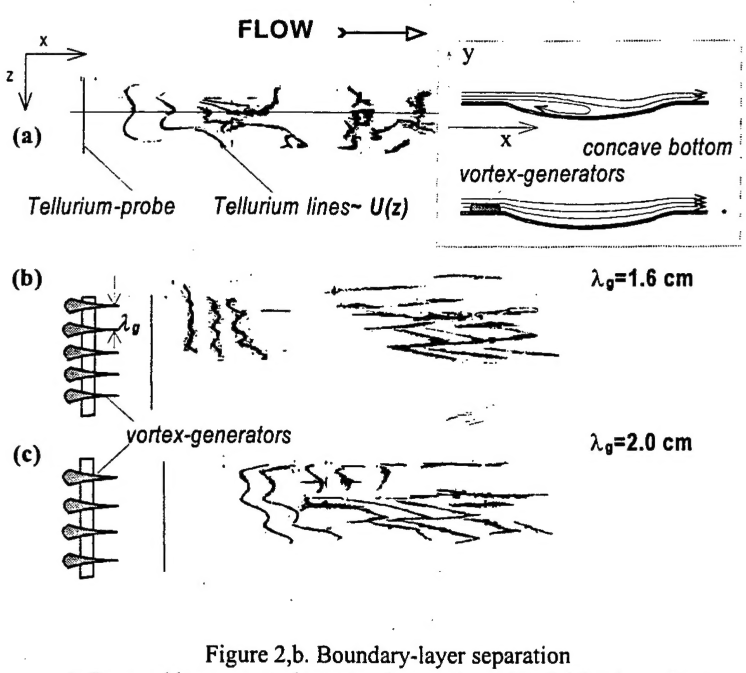



Figure 2,b. Boundary-layer separation influenced by generated streamwise vortices, $U_0$=0.07 m/s, $s$=4 m: (a) natural boundary-layer separation; (b, c) streamwise vortices generated at the edge of a concave test-plate section.

Figure 3 explicitly shows the boundary layer receptivity to the scale of generated vortices, or what can happen in the flow if its basic parameters mismatch the scale of generated vortices: opposite to the adequate response in relation to the scale of generated disturbances ($\lambda_g=\lambda_z$), one can observe either fast attenuation of generated disturbances or a subharmonic response ($\lambda_z=n\lambda_g$). The latter is

well displayed in the case (b) as the modulation of a large-scale natural $U(z)$ wave, $\lambda_0$, with a smaller-scale generated structure, $\lambda_g$, or as the superposition of the two waves. However, the same generation conditions appear to be more appropriate for the greater $Re$, case (c) where the boundary layer maintains the smaller scale vortices too: $\lambda_z \approx \lambda_{g2}$=1.6 cm.

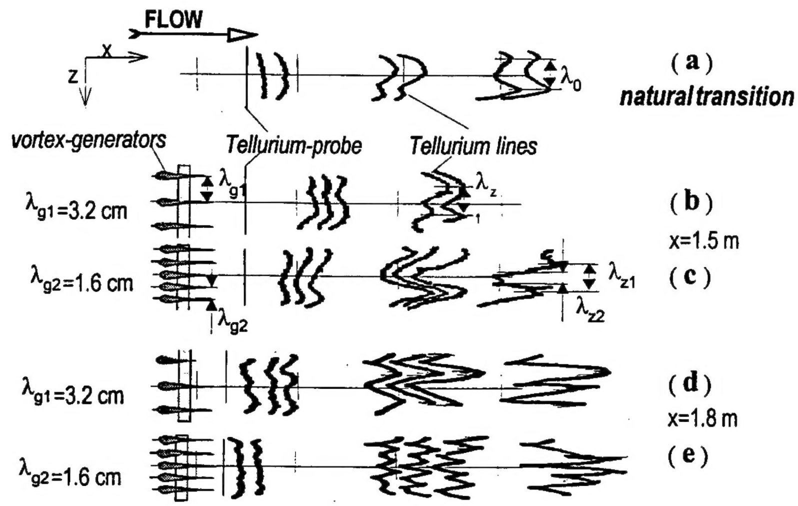



Figure 3. Selective response of a boundary layer to the scale of generated streamwise vortices,
visualized flow field patterns, top view; $Re$=6·10$^4$, $R$=12 m.

Visualized U(z) velocity profiles proved to be a very sensitive and convenient characteristics for such express-estimations of a boundary layer response to a certain excitation and, subsequently, to the choice of the control parameters. That is why the approach of the velocity field visualization in $xz$-plane was used to obtain experimentally the curves in the Goertler diagram of neutral, $\beta^*$=0, and maximum, $\beta^*_{max}$, growth rates of vortices characterized by nondimensional scales $\Lambda_0$ and $\Lambda_{max}$ $(\Lambda=\lambda_z^{3/2}U_0\nu^{-1}R^{-1/2})$, as well as to study possibilities of the active boundary layer control using the thermal modeling of ribs or riblets. From the viewpoint of the boundary-layer control, the Goertler diagram (Figure 4) quantitatively summarizes the selectivity of a bounded flow affected by centrifugal forces to the scale of incoming vortical disturbances.

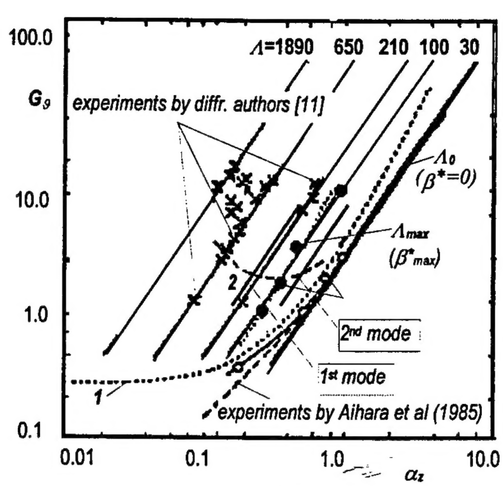



Figure 4. Goertler diagram ($G_\vartheta=\vartheta^{3/2}\,U_0\nu^{-1}R^{-1/2}$, $\alpha_z=2\pi/\lambda_z$);
1 - numerical results by Floryan & Saric (1982),
2 - by Hall (1983) [40];
$\Lambda_0$ and $\Lambda_{max}$ - the authors' experimentally obtained scales of vortices with zero and maximum growth rates;
1$^{st}$ and 2$^{nd}$ modes (corresponding to $\Lambda_1$=236, $\Lambda_2$=84) considered in the numerical simulation below

Another way to impose a desirable vortical structure with a favorable space-scale, or thermal modeling of a ribleted surface, was implemented under very weak heating of longitudinal strips.

Figure 5 shows visualized vortex patterns of the boundary layer over a concave test plate with the flush-mounted strips modeling thermally a ribleted surface. Its effect in a form of typical wavy $U(z)$ distributions is noticeable only in the very vicinity of the surface to realize the condition of small disturbances.

Comparison with the effect of mechanical vortex-generators used for the Görtler stability studies (see Figure 5, h-j) confirmed the mild influence of the thermal strips. However even small disturbances induced by the heated strips proved to be sufficient to modify the large-scale, large-amplitude, nonstationary and irregular natural velocity distributions (a, b) into a smoothed pattern.

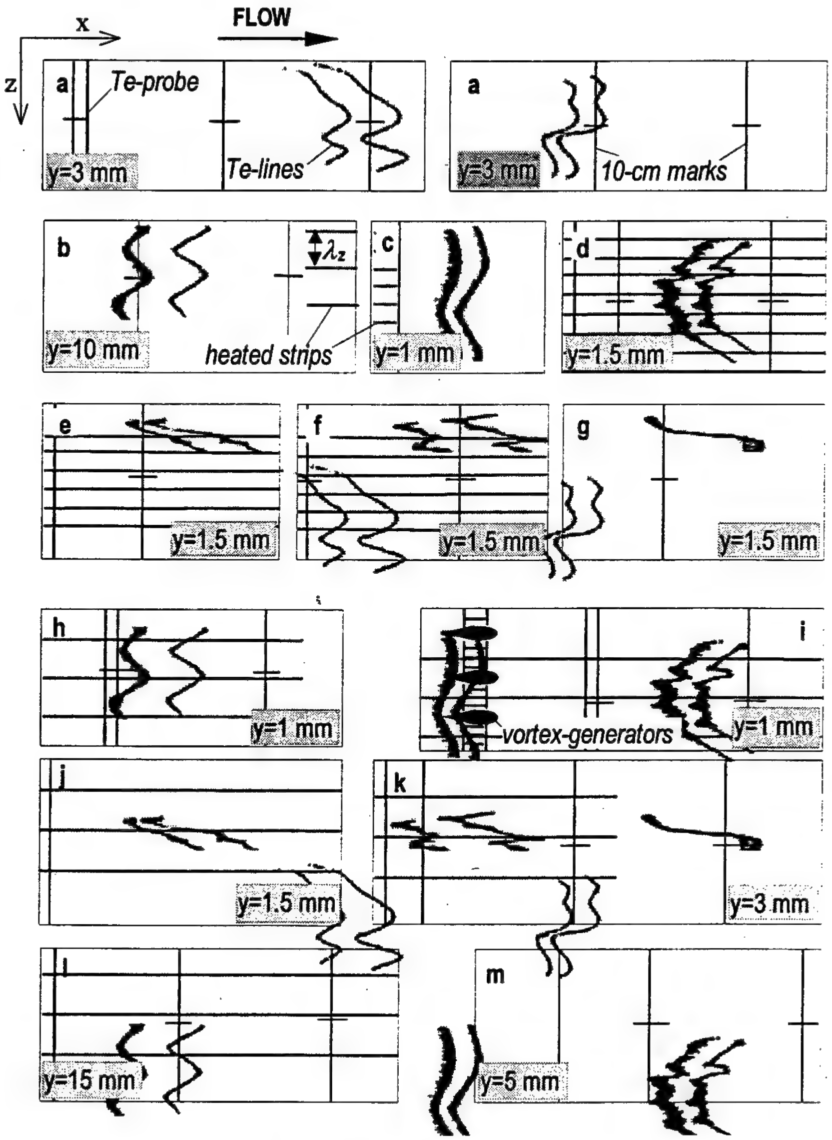



Figure 5. Visualized boundary-layer flow field (top view) over a concave surface, $R$=12 m:
natural laminar-turbulent transition upstream of the ribleted section,
a - $Re$= $0.36\cdot 10^5$ and b - $Re$=$0.5\cdot 10^5$;
flow development with vortices generated by flush-mounted thermal strips
c, d - $Re$=$0.7\cdot 10^5$, $\lambda_g$=1.2 cm, $L$=2 cm and 20 cm respectively;
e, f, g - $\lambda_g$=1.2 cm, $L$=20 cm, $Re$=$10^5$, $1.4\cdot 10^5$, $1.5\cdot 10^5$
and by thermal strips together with "counter-phase" vortex-generators
h-m - $\lambda_g$=2.4 cm, $L$=20 cm, $Re$=$(0.6\text{-}0.7)\cdot 10^5$; m-downstream of the ribleted section.

The latter was observed both in the upper (l) and downstream (k, m) parts of the boundary layer, both under the "concentrated" (short strips, $L$=2 cm) and "distributed" ($L$=20 cm) conditions of thermal excitation (correspondingly c, d). At the same time, the boundary layer showed the tendency to support larger scale vortices transforming the introduced small-scale vortices to the dominating vortical scale as it was demonstrated in Figure 3,c.

In addition, experiments were carried out over a surface with the thermally activated longitudinal "ribs" flush-mounted in a rubber-like layer (compliant coating). The surface compliance is known to smooth the boundary-layer response to any outcoming disturbances [3, 5, 48], i.e. requiring greater disturbance amplitudes or greater $\Delta T$ values to obtain an effect comparable to one on a rigid surface. Therefore there

were three values of the strips temperature used in the experiments: $T_0$, the temperature of the environment (without the voltage applied), $T_1$ corresponding to the voltage $V_1$, and $T_2$ corresponding to the voltage $V_2$.

The compliant section with the thermal ribs, 1 m long, was mounted as a part of the 3 m long rigid bottom of a water channel [47] at x=2.18 m from its leading edge; any other test sections could be inserted there (e.g. a similar compliant homogeneous one) to provide identical experimental conditions for comparative measurements.

Figure 6 shows experimental results displaying the influence of the thermal excitation by heated strips on a near-wall flow structure. Visualized flow field patterns (top view) were obtained under similar flow conditions to those depicted in Figure 5, i.e. $Re \sim 10^5$ and the surface curvature radius $R$=12m.

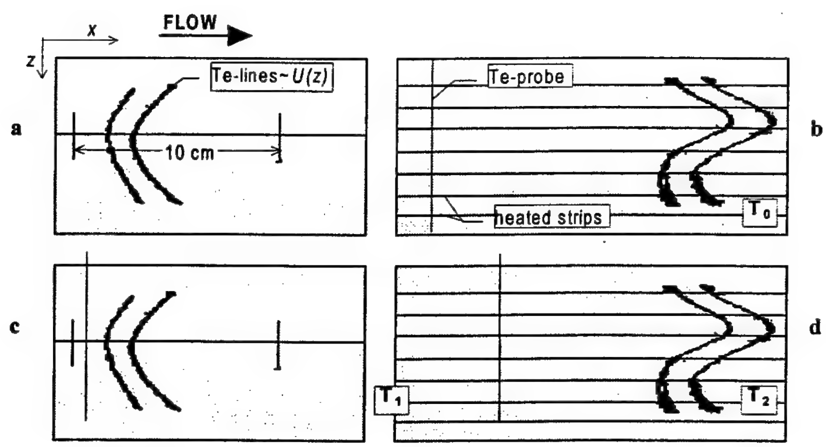



Figure 6. Near-wall visualization of a boundary layer over a concave compliant surface, $Re \sim 10^5$ (U=5 cm/s, x=2.18 m); $R$=12 m; $y$=2 mm:
a - natural development of transition;
thermal excitation by the longitudinal strips $\lambda_g$=1.2cm:
b - the strips are not heated, $T = T_0 = 20°C$;
c, d - the strips are heated correspondingly to $T_1$ and $T_2$ ; $T_2 > T_1 > T_0$

The first pattern (Figure 6,a) shows a nonstationary large-scale vortical structure naturally developing in a transitional boundary layer over a smooth compliant surface. The available $z$-periodic properties of the surface (disguised rigid ribs, Figure 6,b) though immersed into the coating layer, stabilize the $U(z)$ velocity distribution hampering the initially developing meandering motion in the boundary layer; however the amplitude of $U(z)$ stays large enough which indicates a fast course of transition to turbulence.
Moderate heating (corresponding to the value of electric power $P_1$=7.8 W) straightens the $U(z)$ velocity profiles having yet almost twice larger scale than one induced by the thermal ribs; it indicates that the transition process is slowing down compared to the undisturbed case (Figure 6,c).
Increased due to stronger heating ($P_2$=12.2 W) keeps the averaged $U(z)$ distribution straightened along a whole length of the ribbed section and downstream; in addition, it generates the smaller-scale vortical structure following the scale induced by the thermal ribs (Figure 6,d).

Thus the obtained results show that choosing the values of controlling parameters, such as $\Delta T$ and $\lambda_z$, in correlation with the basic flow parameters, one can reach a desirable effect in a boundary layer: ***the stabilized smoothed velocity field development or induced vortical structure with a given scale, short or long-term effects.***

## 5. NUMERICAL SIMULATION

### 5.1. Formulation of the problem. Methods. Basic parameters.

The numerical study aims at revealing physical mechanisms of the formation of vortices induced by the heated strips and its dependency on different regimes of thermal excitation. Moreover, given a flow situation with relative body- and viscous forces comparable to the experiment, the simulation is to show that the described effect of thermal ribs is seen in the case of compressible air flows as well.

The numerical approach is based on a code developed for the direct numerical simulation of the laminar-turbulent transition in compressible subsonic boundary layers [12, 33]. It was successfully applied to study disturbances of various nature like vorticity- , temperature- and density near-turbulent fluctuations [13, 14]. The viscosity dependence on temperature is implemented due to Sutherland's law for air. The code employs the spatially periodic model for the stream- and spanwise directions. Correspondingly, the flow quantities $v$- specific volume, $m_i$ - momentum in direction $x_i$ and $e$- total energy are expanded into Fourier series in the wall parallel directions. The choice of this set of dependent variables allows a formulation of the Navier Stokes equations, in which all generic nonlinearities (Euler terms) occur as products, such that aliasing errors can be exactly eliminated [12].

A highly ($6^{th}$ order) accurate compact finite difference scheme [12, 24] discretizes the wall normal direction while a spectral formulation is used in the other directions.. The evolution in time $t$ is represented numerically according to the Crank-Nicolson scheme. The resulting nonlinear equation system is solved within second order in the time step (prescribed as to guarantee numerical stability and accuracy) employing a classical Richardson iteration with 3 steps.

The present application of the code to the boundary layer control by thermally modeled ribs is enabled by the specification of a spanwise periodic temperature boundary condition and the inclusion of body force terms. The numerical procedure can be described in the following way. For times $t<0$, the disturbance-free flow is subject to (constant, uniform) adiabatic temperature wall boundary conditions. At $t=0$, a z-periodic wall temperature field with a specified temperature difference $\Delta T$ with respect to the laminar adiabatic wall temperature is switched on. As a consequence, the flow responds by establishing a vortical structure with a corresponding change in the mean momentum distribution across the boundary layer.

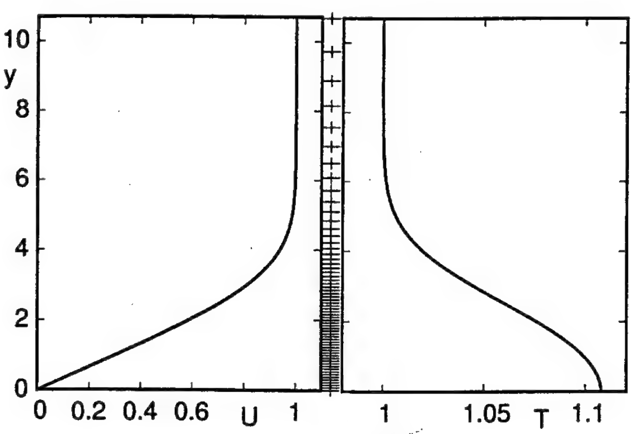



Figure 7. Undisturbed flow at the beginning of simulation. Left: velocity $U(y)$, Right: Temperature $T(y)$.

Simulations were carried out for a Goertler number of $Go_d = 15$, and a Reynolds number of $Re_d=595$, where both parameters are based on the Blasius reference length $d=(\nu_o x / U_o)^{1/2}$. The spatial scales are non-dimensionalized in the same way, and time is non-dimensionalized with $d/U_o$. The free-stream Mach number considered is $M=0.8$, the free-stream temperature is $T_o=290$ K, the medium is air with constant isentropic exponent $\gamma=1.4$ and Prandtl number $P=0.71$. The velocity and temperature profiles of the undisturbed flow are given in Figure 7. The momentum thickness $\vartheta$, based on this profile is $\vartheta = 0.66\ d$, such that the corresponding Goertler number based on $\vartheta$ is $Go_\vartheta = 8$. The fundamental in the spanwise direction was taken to be $\alpha_z=0.66$, corresponding to $\Lambda=236$, i.e. from the range of most amplified disturbance wavelengths (see Goertler diagram, Figure 4). Given this fundamental mode wavelength, the second harmonic corresponds to $\Lambda=84$ and thus is still in the domain of amplified disturbance wavelengths, while all further harmonics are linearly non-amplified. Twelve harmonics were found to resolve the flow patterns sufficiently for all simulations.

Direct Numerical Simulations (DNS) were carried out for a variety of thermal excitation cases, the results of which are presented in the following chapter. It is emphasized that for none of the considered cases an initial condition was specified which would correspond to a pre-computed Görtler eigenfunction, taken from a linear stability analysis. Any initial disturbance of the flow was introduced exclusively in the form of a change in the wall temperature because the disturbance initiation according to linear eigenfunctions would be a too idealized scenario in order to be realizable in a real situation. The introduction of only a temperature disturbance required the vortex system to self-establish without any pre-determination except for the imposed spatial scale in the spanwise direction. The following main two cases of thermal excitation of vortices were considered in detail:

***Case 1:***
Taking the spanwise space-scale of a longitudinal vortex pair close to the most unstable according to linear theory as a reference, the strips were placed so that to ideally excite the second harmonic and harmonics thereof. The wall temperature was fixed at $\Delta T=30$ K above the recovery temperature of the initial, disturbance-free flow at $0<z<1.54$ and $3.08<z<4.62$ (all lengths non-dimensionalized with $d=(\nu_o x/U_o)^{1/2}\approx 1.52\ \vartheta$, with $\vartheta$-momentum thickness). Also, a small initial wall temperature variation of about 0.3 K along the spanwise direction was introduced, including components of the fundamental mode, in order to account for small imperfections.

***Case 2:***
The first strip of case 1 was slightly shifted in the spanwise direction, thus introducing a permanent direct forcing component on the fundamental mode. So the heated strips were placed at $0.13<z<1.67$ and $3.08<z<4.62$.

***Case 0:***
As a reference to the thermally forced cases the unforced evolution of Görtler vortices was computed also, i.e. no permanent thermal forcing at the wall was imposed. The wall was homogeneously kept thermally perfectly insulated. The flow parameters were specified in the same way as in the computations for the forced vortex excitation and maintenance. A very small initial pulse disturbance ($10^{-10}$ in amplitude w.r.t. mean quantities) was introduced to keep the system in the linear regime for a very long phase. Thus, "generic" Görtler vortices could arise and evolve free of any transients.

### 5.2. Results and discussion

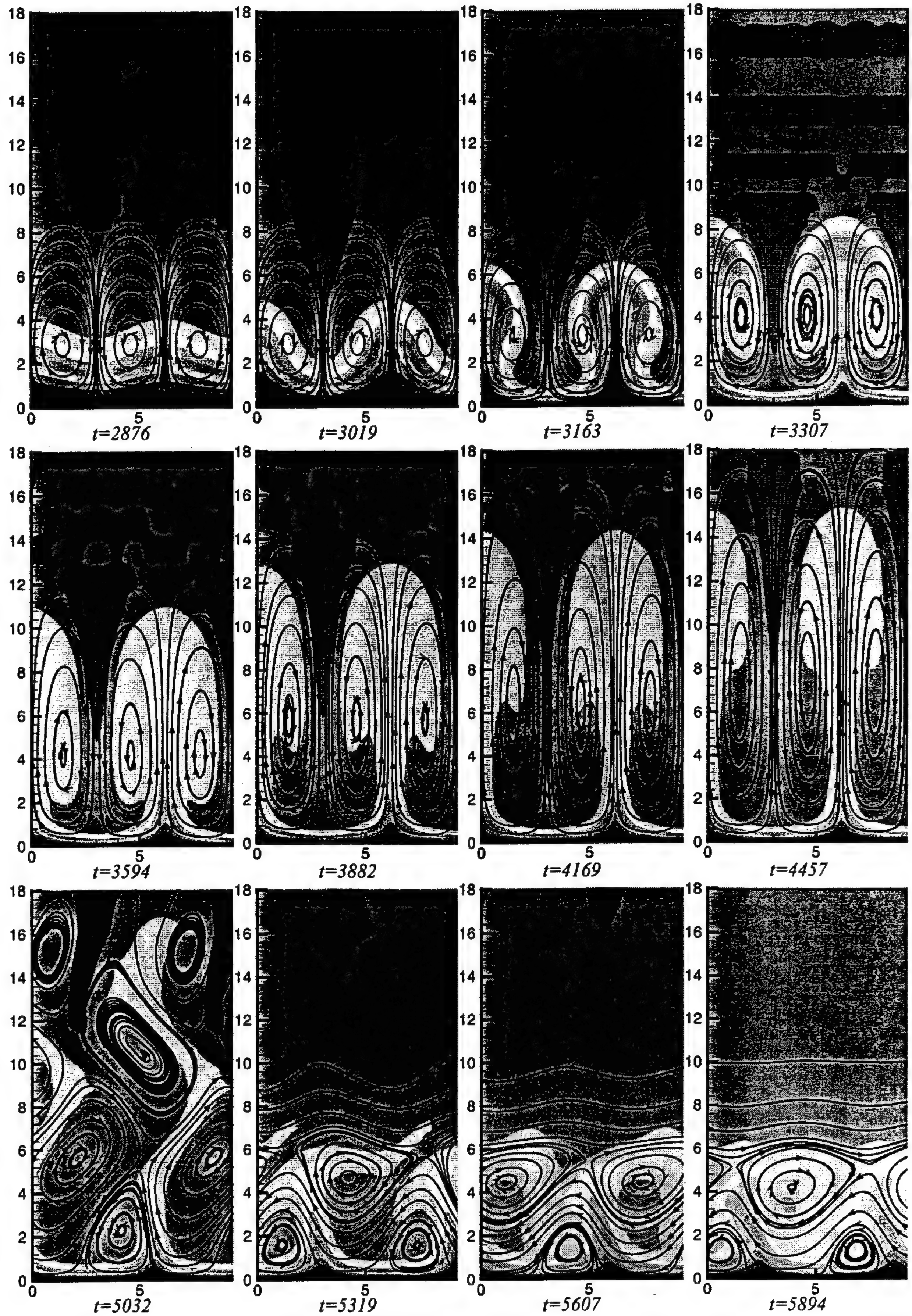
First of all, a physical picture was considered of the natural emergence, development and breakdown of the vortical structure. The boundary-layer flow structure was visualized in a process of its unforced evolution (case 0) and presented as a sequence of the flow field patterns in *yz*-plane. It included the very late stages of the evolving vortices (i.e. beyond the breakdown of the classical Görtler-type vortices). Then the vortex system formation and development under thermal forcing (cases 1 and 2) was studied, e. g. in a form of the observed delay of the vortex breakdown. Specific features of the two considered forcing regimes were analyzed.

As it was mentioned above, the case of thermally unforced vortex emergence (case 0) is to serve as a reference for the further discussed scenarios. Figure 8 shows the evolution of the case 0 flow structure. It can be seen that the vortical structure development displays at least four distinct phases described accordingly as {1} Vortex emergence, {2} Vortex growth, {3} Vortex breakdown, and {4} Vortex post-breakdown.

Here, the "***emergence***" of the vortical structure is understood as the boundary-layer flow development between initiation of disturbances until the moment when a saturated level of the modes-amplitudes is established. At this stage, non-linearly saturated Görtler vortices have been generated. During the emergence-phase the initial disturbance transients decay, while preferred signal components are selected by the flow to amplify and to create the paticular vortex system.

{1} The emergence phase ranges up to about $t=3163$ (first three pictures of figure 8). One obvious characteristic of the emergence phase of the Görtler vortices is, that the overall vortex size and the vertical position of the vortex core remain invariant, although the amplitudes are increasing. The skin friction coefficient stays almost unchanged during this whole phase.

{2} The vortex growth phase is characterized by the fact, that the disturbance amplitudes are saturated. Thus during this phase energy is only non-linearly re-distributed among the modes, whereas in the emergence-phase a continuous increase of mode energy was observed. In terms of the flow topology, this non-linearity is expressed as the development of the mushroom-like vortical structure formed by the low-momentum fluid uprising from a wall. The validity of the observed effect and its interpretation is confirmed by earlier investigations [38].



t=2876
t=3019
t=3163
t=3307
t=3594
t=3882
t=4169
t=4457
t=5032
t=5319
t=5607
t=5894

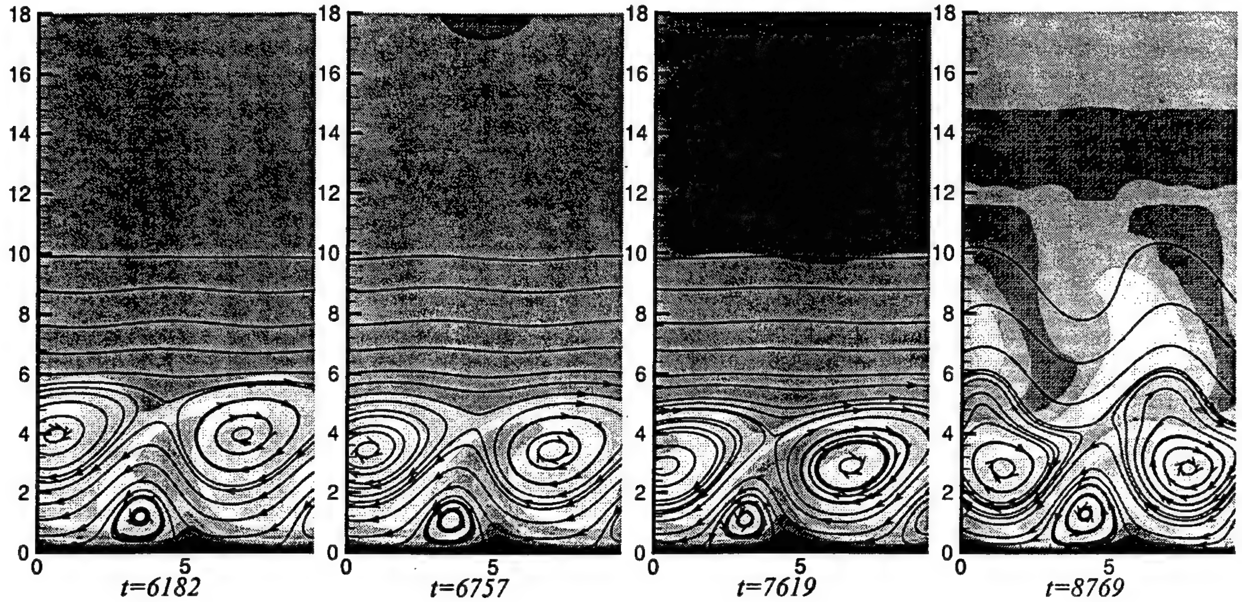



Figure 8: Evolution of vortex structure under the natural boundary-layer flow development (case 0): vertical = wall normal direction y, horizontal = spanwise direction z; the streamwise velocity component is visualized in color-contours (darkest blue = 0.1; deepest red = 1.1. The contour step is 0.1).

The evolution of the saturated-amplitude phase is observed roughly in the range of before $t=3307$ and $t=5032$, as shown in Figure 8, i.e. for $t_0 \approx 1700$. The pictures 4 to 8 of Figure 8 (see time stamp below each picture) are a sequence of snapshots of the vortical structure in the vortex growth phase. While the vortex shape stayed invariant for a long time in the emergence phase (pictures 1-3, Figure 8), the onset of the vortex growth phase is indicated by an almost linearly in time occurring vortex elongation in the wall normal ($y$) direction. Accompanied with this growth, a lift of the vortex centers away from the wall is observed from about half the original boundary layer thickness to a height well beyond the original boundary layer thickness. The vortices reach far out into the free-stream and transport high $x$-momentum fluid into regions close to the wall. As a consequence, during the whole scenario the skin friction coefficient raises by a factor of 5 or so, before it starts to decay again.
The vortex growth phase ends with an overall collapse of the vortices.

It should be mentioned that the vortex growth phase is very important in terms of possible practical applications, since during this time a well established, stable vortex system is self-sustained. This very flow situation can be used, e.g. for the separation control due to enhanced mixing of streamwise momentum.

{3} All simulations have shown a finite life-time of the Görtler vortex system. In all cases a real collapse, i.e. an extremely rapid breakdown of the vortices takes place.
There are two main features in which the vortex fields differ before and after the breakdown (compare pictures 8 and 10 of figure 8):
a). the vortices after the breakdown are certainly much more compact (more circular); their height is reduced to less than a third of the height before the breakdown,
b). the vortex pairs, consisting of two adjacent counter-rotating vortices become asymmetric; one of the two grows in size and strength for the expense of another one.
It has been observed that the decision, whether the clockwise or the anti-clockwise rotating vortex "wins" in the deformed pair is a matter of most minor initial random perturbations (initially of the order of the average computer error). During the breakdown, the vortical system flips over to one side and subsequently stays in this shear asymmetry. Hydrodynamic instability mechanism can be supposed to work here due to the strong vertical shear layers between the pre-breakdown elongated counter-rotating vortices creating the locally jet-like flows and, as a result, inflexional velocity profiles.
For explicitness, the successive stages of the vortical system evolution process are sketched in figure 9.

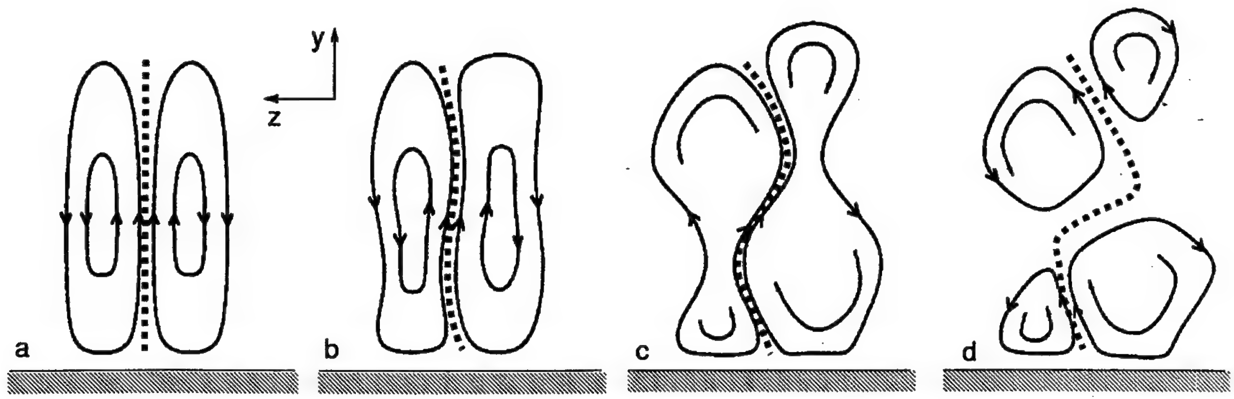



Figure 9. Scenario of the natural evolution and breakdown of the streamwise vortical structure:

a) vertical (strongly unstable) shear layers between two counter-rotating vortices,
b) vortex shape deformation due to an amplified instability mode of a shear layer,
c) aggravation of the vortex deformation / restriction of their amplitude under the action of the instability,
d) breakdown of the vertically stretched vortices into new, compact structures
(near wall vortices survive under centrifugal forces, while upper vortex parts decay).

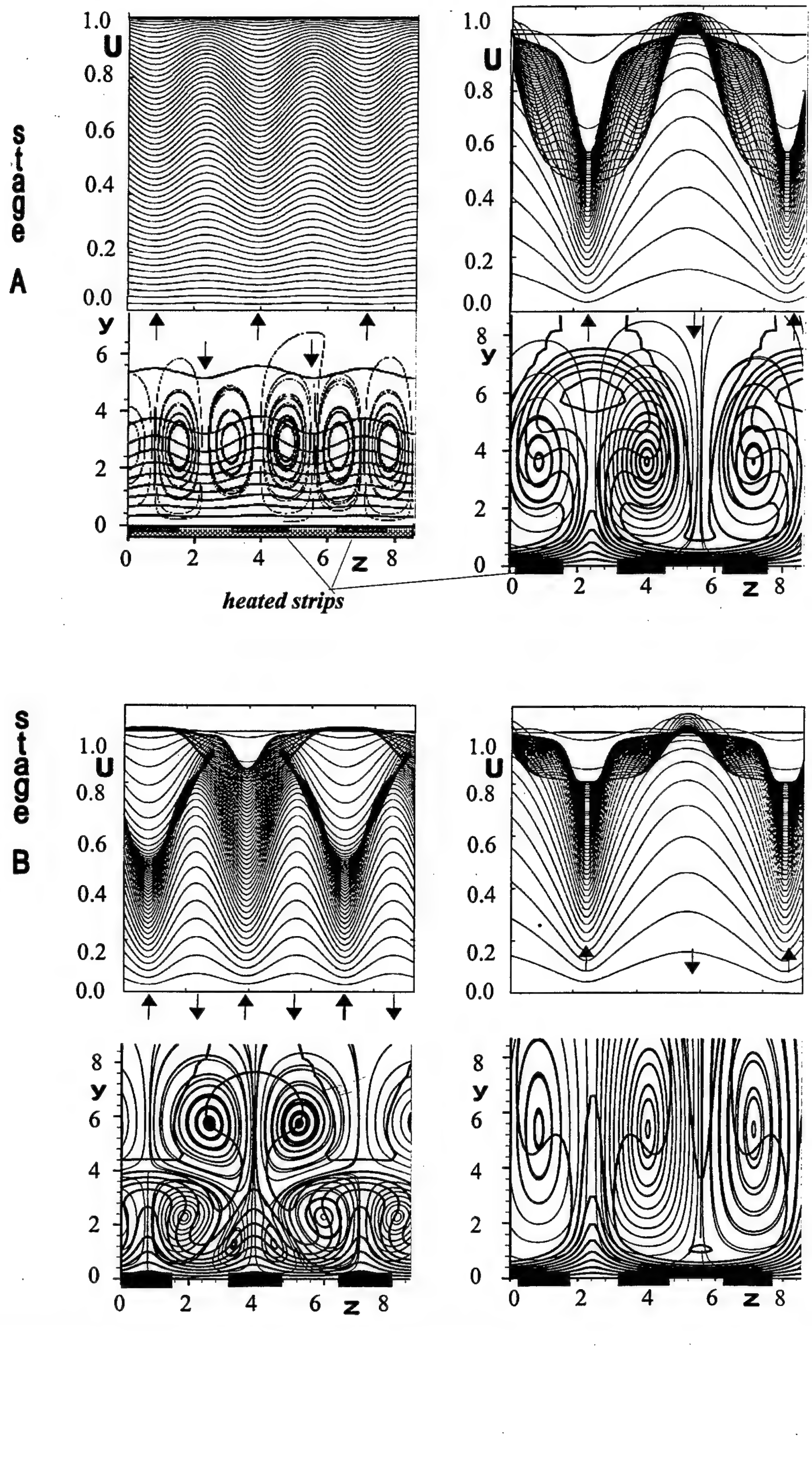
{4} The way leading to the vortical system breakdown defines the characteristics of the post-breakdown vortex system. For instance, the stage in Figure 9 between the stages (c) and (d) is visualized in pattern 9, Figure 8, where the mushroom-structure of the original, stretched vortices is still seen, though in a strongly S-shape-distorted form.
As described above, the vertically stretched Görtler vortices inevitably collapse into asymmetric, compact vortices. This new vortical system settles down not to an asymptotic but only to "quasi-asymptotic" state. It was shown by the simulations carried out far beyond the vortex breakdown stage. They demonstrated the repeating sequence of events visualized in Figure 9 sketch: the reconstruction of the vortical structure after "bursts", the phenomenon similar to one known in sublayers of turbulent boundary layers.
Here, it was found to be always accompanied by a rise in the skin friction coefficient.

***Effects of the thermal excitation*** using the flush mounted heated strips are discussed below.

Like for the natural vortex evolution (case 0), the forced vortex development is considered consisting of the emergence- and growth phases, shown in Figure 10 as the spanwise variation of the streamwise velocity component $U(z,y_p)$ coupled with the flow topology for three subsequent stages of the vortex formation (*A–C*) identified by the simulation time. The normal positions $y_p$ (distances from the wall) at which the profiles are taken, are indicated between the two diagrams of Figure 7. Cases 1 and 2 are represented correspondingly by left and right columns.

As displayed in Figure 10 (top left), the purely second-harmonic forcing of case 1 initially causes a respective near-wall flow reaction in a form of the generated small-scale structure, $\lambda_z=\lambda_g$. For case 2 (top right), the distorted excitation introduced by the slight displacement of one of the heated strips governs the vortex formation process due to the additionally induced fundamental mode; this is already apparent from the very early stages of the vortical structure evolution. Later stages of the vortex formation process are shown in the center and bottom parts of Figure 10. The gradual transformation of the initially generated flow structures to larger scales, corresponding to the fundamental wavelength is seen. Since equal simulation flow times are considered for the two cases, it can be conjectured, that there is a strong influence of the excitation scheme on the near-wall region and on the early vortex formation (or shortly downstream in the similar spatial experimental tests). In the middle term (or farther downstream in experiments), the natural vortex scale prevails which corresponds to the fundamental mode. It is also seen that the rate of the vortex formation process strongly depends on the type of forcing, or the arrangement of the heated strips, i.e. their regular or irregular arrangement along $z$.

Thorough analysis of the obtained simulation results for both cases 1 and 2 (similar to those presented in Figure 8 for case 0 but not shown here) yielded more details dealing with the possibilities of the boundary-layer control using specially organized surface temperature fields.



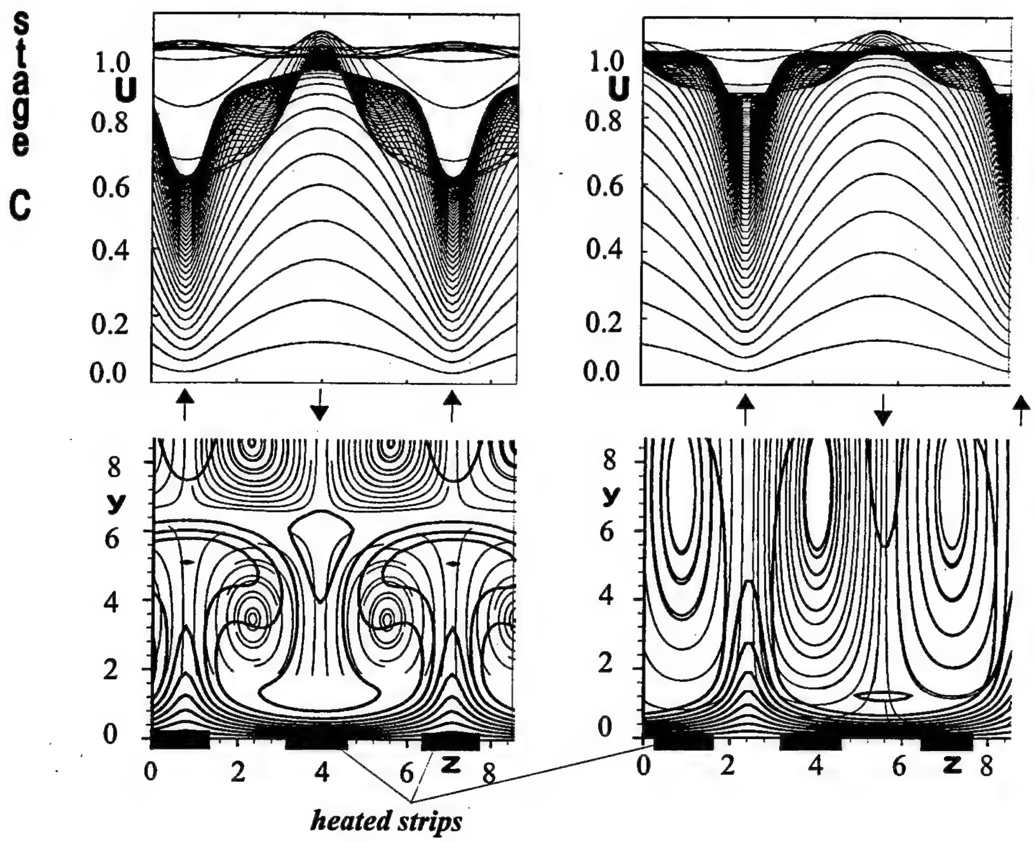



Figure 10. Streamwise velocity profiles $U(z,y_p)$ for the two cases considered at three consecutive stages of the vortical systems formation: flow times $t$=1150 (stage ***A***), 1725 (stage ***B***), 2300 (stage ***C***).

In particular, it was found out that the emergence phase for the both 1 and 2 cases is less regular compared to case 0, since here, finite amplitude transients appear due to the more realistic sudden switching of the small, but finite thermal forcing at the wall.
The initiation of the vortex system in case 1 is primarily due to pure second harmonic forcing (wall temperature disturbance, containing components of $2^{nd}$, $4^{th}$, $6^{th}$, $8^{th}$, $10^{th}$ and $12^{th}$ mode). The emergence phase (including the formation of the dominant larger scale vortices, Figure 10, stage ***B*** left) in this case is finished at a time of about $t=1800$.
For case 2, defined by a slight shift of one of the thermal strips of case 1, a small fundamental forcing component comes into play additional to the even number mode forcing of case 1. Although again (as in case 1) the second mode has larger amplitudes as the fundamental mode initially, the first mode takes over very rapidly and leads the vortex system into saturation extremely fast. At about t=1100 the emergence phase in case 2 is finished. At the very end of the emergence phase of case 2, about the same vortex system is established as in case 0 at about $t=3300$.

The effect of the control of the vortex system by means of thermal strips can be seen in the vortex growth phase: it is definitely extended compared to the unforced case. This means that a well established, stable vortex system is available for flow control purposes for a longer period. The obtained simulation results show that for case 1 the vortex growth phase ranges from about $t=1800$ to $t=4300$, i.e. for a period of $t_1=2500$. As in case 0, the skin friction coefficient grows here, but less rapidly. Besides, it reaches lower peak value (about 90% of the unforced case).
For case 2 the vortex growth phase appears still longer compared to the unforced vortex growth though shorter than for case 1. It can be conjectured to start at about $t=1100$ and range up to $t=3300$, leaving an overall period of about $t_2=2200$. The maximum skin friction value during the vortex growth phase of case 2 is a little higher, compared to the unforced vortices. The duration of the vortex growth phase in both thermal control cases is significantly larger than the value $t_0=1700$ obtained in the unforced case. For the second harmonic forcing (case 1) this indicates that the downstream length of a stable, well established vortex system appears extended

by about 47% and for the shifted strip (case 2) by about 29% compared to the unforced case. This effect is remarkable in view of the rather moderate heating requirement for in either of the two cases the temperature on the strips was raised only by an amount of $T=30K$ above the (natural) adiabatic wall temperature.

From the fundamental viewpoint, one may conclude that the forcing influences the very instability mechanism leading to the vortex collapse, since the thermal forcing due to the strips has obviously extended the phase of existing streamwise vortices.

From the viewpoint of applications, obtained estimates confirm the expected effect of the thermal strips to control the vortex dynamics in the near-wall flows depending on the parameters of induced perturbations.

In relation to other control parameters of the system, the heated strips of half width of those in cases 1 and 2 and operated at twice the value of $\Delta T$ were investigated. Preliminary simulations indicated no strong effects on the initial phases of the vortex formation but considerable changes of the long-term phases of the boundary-layer vortical structure.

### 5.2. Joint analysis of experimental and numerical results

Fundamental experimental and numerical investigations were planed and carried out so that to match basic flow parameters and, accordingly, to obtain physically comparable results. However peculiarities of the experimental facility and techniques applied stipulated certain restrictions to the values of parameters. In particular, the electrochemical Tellurium-visualization method is known to work reliably in water flows at free-stream velocities $U_0$<0.2 m/s. Therefore, non-dimensional flow parameters such as Reynolds and Goertler numbers were limited. For instance, in experiments– 5.0 while in the numerical simulation, $G_\theta$=8.
Nevertheless, the space scales of thermally forced vortical structure were chosen in both cases to correspond the second harmonic according to the linear Goertler theory. It means that the evolution was studied of non-dimensional vortices characterized by $\Lambda_2$=84 (for reference, see Goertler diagram of Figure 4, blue lines). Besides, a wide range of vortex space scales generated in the experiments using mechanical vortex-generators enabled direct qualitative analysis of experimental and numerical visualizations of the induced vortical systems. To show correlations of the parameters in the non-dimensional domain, it can be noted that experimental visualization patterns presented in Figures 3, 5, 6 are obtained for $G_\theta \approx 4.5$ and correspondingly, $\Lambda_0$=31 (in the vicinity of the neutral curve, i.e. for the scale of the vortices not decaying and not growing ) and $\Lambda_2$=88 (2$^{nd}$ harmonic) for Figure 3, $\Lambda_0$=29 and $\Lambda_2$=82 for Figure 5, $\Lambda_0$=29 for Figure 6. These references facilitate physical interpretation of experimental data and their comparison with the numerical results.

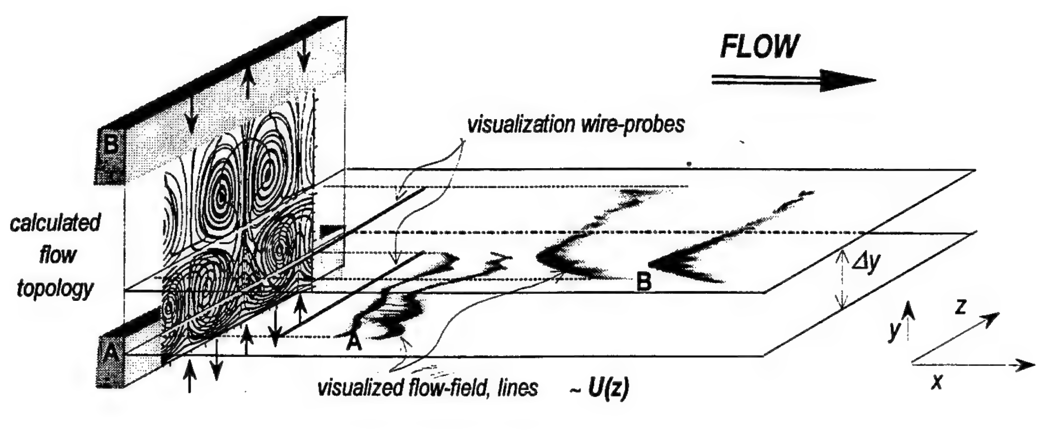



Figure 11. Vortical structure transformation across a boundary layer – calculations (left) and experiments (right) :
from a small scale **A** near the surface to a larger scale **B** in the outer region;
experiment: $Re_x$=0.6·10$^5$, $y_{lower}$=0.1 cm, $\Delta y$ =0.3cm

Thus, the joint analysis of experimental and numerical results provided the fundamental basis for the formulated flow control purposes having revealed mechanisms of the vortex dynamics of boundary layers under body forces, in particular, in a form of their response to generated streamwise vortices of a given scale depending on the basic flow parameters. The investigations based on the Goertler stability approach, i.e. for boundary layers affected by centrifugal forces, yielded a set of results which are in a good agreement both with each other, and with known simulation results [26].

Computational and experimental data were compared by evaluating the streamwise velocity component $U(z)$ at various heights $y_p$ for subsequent stages (identified by the simulation time) of the vortical system development as well as the flow topology (iso-velocity stream-traces in the plane normal to the flow direction). The transformation of the vortices induced on the wall to larger scales in the outer boundary-layer region is presented in Figure 11 as a combination of numerical and experimental results. It was found out that in the middle stages of the vortical structure evolution, both sets of the obtained data showed that the thermally induced small-scale structure can be maintained up to $y \leq 0.4\delta$. It is seen from the transformed $U(z)$ velocity profiles and from the flow topology.

As well as in a normal to the flow direction plane, a similar effect was observed in the flow structure development in time (or downstream in the experiments). It is especially well seen in case of harmonic excitation. For comparison, one can see, for example, Figure, 3b that shows vortices initiated with $\lambda_{gz}$=1.6 cm which develop downstream into a larger scale vortical structure with the spanwise space-scale of $\lambda_z$=3.2cm.

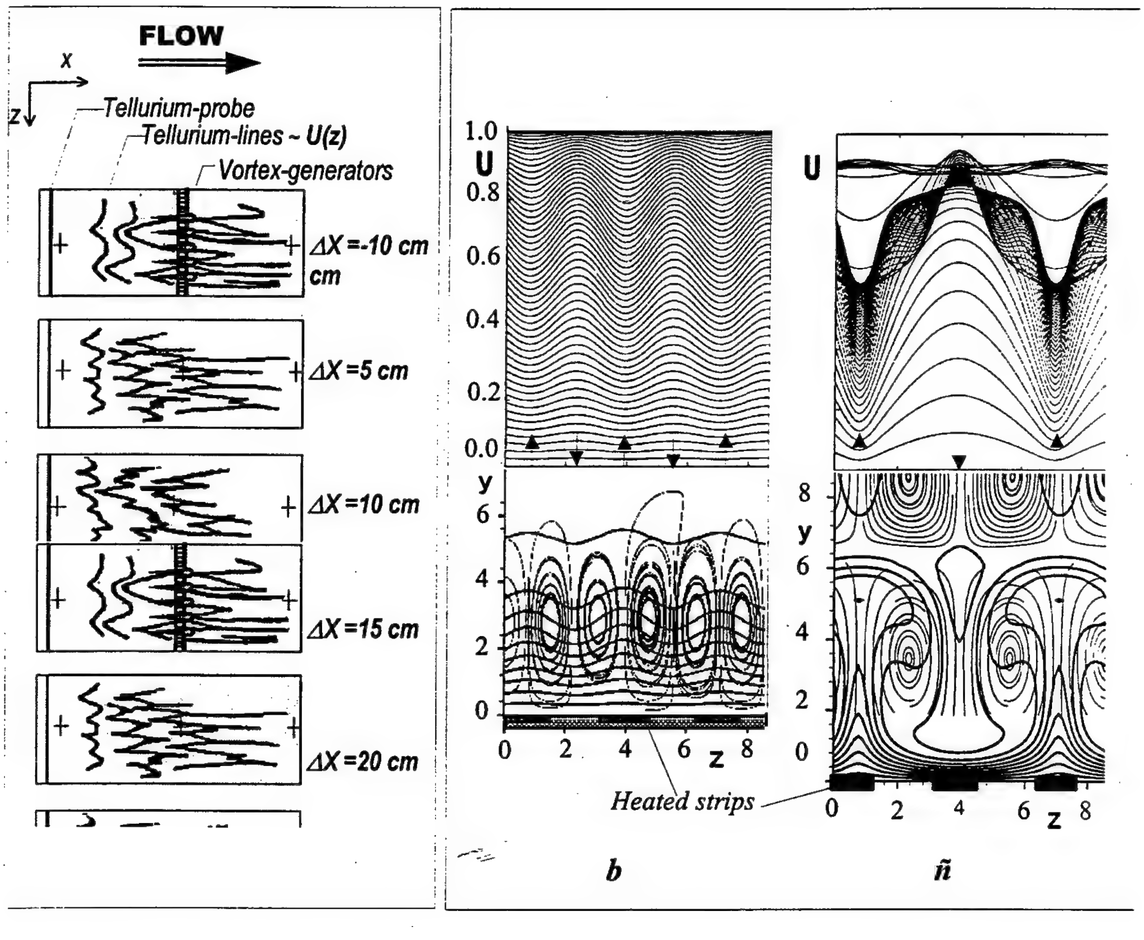



Figure 12. Downstream/temporal scale transformation of longitudinal vortices generated in a boundary layer:
***a*** – experiment (downstream flow-structure development), $Re_{X0}=0.6 \cdot 10^5$ (vortex-generators), $\Delta X = X_0 - X_{probe}$, $y$=0.2 cm, $\lambda_g$=1.2 cm;
***b***, ***c*** – calculations (temporal development), consecutive stages for flow times $t$=1150 (stage ***b***) and 2300 (stage ***c***).

Figure 12 gives a possibility to observe directly the mentioned downstream scale-transformation process in terms of experimental (left) and numerical (right) results. Both experimental, and numerical visualization of the velocity field has explicitly demonstrated that the life-time of incoming (or generated by any means) small scale vortices cannot be large if the vortices are "unwelcome" in the boundary-layer flow, i.e. if their parameters are not correlated with the basic flow parameters.

In this connection, from the viewpoint of effective flow control, it gives practical guidelines for the choice of vortex scales to be generated and maintained in boundary layers. Besides, experimentally observed delay of the vortical structure development over the surface with the heated strips (see Figure 5, e-g, j-m, Figure 6, c, d) was confirmed numerically. It was demonstrated as the extension of the vortex growth-phase estimated as 47% in case of the second harmonic excitation ($\Lambda$=84) compared to the naturally developing vortical structure. Experimentally generated vortices with the scale close to the neutral one were shown to evolve even more slowly.

## 6. CONCLUSIONS.

Vortex dynamics of boundary layers affected by body forces was considered as interaction of viscous and body forces (in examined cases, centrifugal forces and buoyancy). Laboratory tests and the asymptotic theory demonstrated that it logically leads to the development of a specific large-scale boundary-layer structure in a form of streamwise counter-rotating pairs of vortices at a downstream position where the vorticity sources caused by viscous and body forces become comparable. The study of the self-organized coherent structures is important both for the basic knowledge of the laminar-turbulent transition and turbulence phenomena, and in particular, of transport processes in bounded flows that brings to direct practical applications of the results.

Joint numerical and experimental studies based on the Goertler stability theory and receptivity of boundary layers to induced longitudinal vortices yielded an insight into the vortical structure evolution having been considered both across the boundary layer and downstream (or in time). The estimations based on this approach and obtained data together with those given by the asymptotic theory explained the fluid motion physics around a low-pressure turbine blade and resulted in the formulation of the problem of the flow field improvement for a concrete practical case. ***The basic idea of optimal flow control is the utilization of the natural dominant structure (streamwise vortices) of the flow under body forces.***

A method was proposed and developed of non-intrusive generation of streamwise vortices with a given scale. It is based on heating of a flush-mounted array of longitudinal elements (strips) regularly spaced in the spanwise direction. Experimental and numerical visualization of the boundary-layer flow field showed the method capacity for flexible management of the flow structure and its integral characteristics. Depending on the boundary conditions given by a distance between the adjacent heated strips and their temperature gradient with an ambient flow, properties of the induced vortex system (space scale, intensity and growth rate) could work in a desirable way. Being generated strictly according to the basic flow parameters, the streamwise vortices were shown either to stabilize the flow situation (extending a phase of laminar-turbulent transition) or to intensify mixing processes near the wall and thus delaying flow separation or enhancing heat transfer.

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The results obtained due to the project implementation were reported at several international conferences and published as the papers listed below that characterizes the interest of the scientific community to the topic investigated, approaches used and the results presented.


1. **"Flow management using inherent transition and receptivity features"**, Yurchenko, N.F., Rivir, R.B., 1998, *Proc. International Symposium on Seawater Drag Reduction*, Newport, USA, 1998.
2. **"Optimization of heat transfer control based on a receptivity approach"**, Yurchenko, N.F., 1998, *Proc. Turbulent heat transfer conference*, Manchester, UK, 1998.
3. **"Active control of boundary layers over riblet surfaces"**, Yurchenko, N., Delfs, J., 1998, *Proc. International Conference on Flow Control*, Goettingen, Germany, 1998.
4. **"Vortex dynamics of boundary layers under body forces: dominating mechanisms and control"**, Delfs, J.W., Yurchenko, N.F., Rivir, R.B., 1999, *Proc. Workshop "Outcomes and Perspectives of Cooperation between the European and Siberian Scientists in a Field of Physical Hydromechanics", Novosibirsk, Russia, 19 - 23 April, 1999.*

5. **"Nonlinear development of the forced vortical structure in flows under centrifugal forces"**, Yurchenko, N.F., Delfs, J.W., 1999, *11th International Couette-Taylor Workshop, Bremen, Germany, July 20th – 23rd, 1999.*
6. **"Large-scale vortices and fluid transport near a wall"**, J.Delfs, B.Ilyushin, R.Rivir, N.Yurchenko, 2000, *3d International Symposium on Turbulence, Heat and Mass Transfer, Nagoya, Japan, 2000, Apr. 3-6 (submitted).*
7. **"Optimization of a turbine blade performance due to active control of vortex dynamics"**, N.Yurchenko, R.Rivir, *NATO/RTO Active Control Symposium, Braunschweig, Germany, 2000, 8-12 May (submitted).*
8. **"Improvement of the turbine blade performance based on the flow instability and receptivity analysis"**, N.Yurchenko, R.Rivir, 2000, *8th Int. Symp. on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC-8), Honolulu, Hawaii, March 26-30, 2000 (submitted).*


## 7. PROSPECTS.

Entailing the transition to turbulence, streamwise vortices must stay a focal point for thorough studies due to a set of reasons.

(1) They are directly connected with a critical parameter of a downstream location of transition that is important for the design of numerous units of engineering constructions, such as, for instance, a turbine blade or an airplane wing.
(2) A dominant and deterministic character of this vortical field combines with memory effects (information transfer about the history and structure of an averaged flow by large-scale vortices). The possibility to give a clear physical formulation of the problem enables its rigorous mathematical description unlike conventional turbulence models based on the conception of isotropic homogeneous fluctuating motion.
(3) Beneficial application of this vortical structure dominant for boundary layers under body forces was shown for the flow control (separation, heat transfer) if the generated vortices are correlated with the basic flow parameters.

Besides, the proposed method of the boundary-layer control using flush-mounted heated strips needs more detailed substantiation of being optimal for bounded flows under body forces, as well as its development for concrete practical applications. It means the elaboration of a more generalized approach which would take into account the role of large-scale vortices in turbulent environment for fluid transport near a wall (with mechanisms which cannot be considered within turbulence models built up on the idea of gradient-type transfer processes).

In this connection, further investigations are necessary

- to study the streamwise vortical structure in spectral terms;
- to analyze the flow response to other excited modes and their combinations considering different size and arrangement of the thermal strips over the surface and different temperature gradients $\Delta T$;
- to obtain normal velocity and temperature profiles evolving in a boundary layer for a set of characteristic conditions of its excitation;
- to observe long-term effects of the different wall heating and to relate it to the internal vortical structure of the boundary layer affected by body forces;
- to consider a possibility to control the spectrum of turbulent fluctuations as well as to adequately and effectively predict distributions of basic statistical flow characteristics, to give estimates of skin friction, heat and mass transfer parameters.

## 8. APPENDIX
### Proposed engineering solution (invention)

Both experimental and numerical data analyzed together with the available published results give the necessary and sufficient fundamental grounds for the elaboration of an optimal engineering solution suitable for direct practical applications. Hence, provided that a formulated new idea is taken as a basis and a starting point, such an engineering solution can compile a subject of an **invention**.

*SUMMARY*

An engineering solution is proposed for the device and method of the active boundary-layer control based on preferred-scale counter-rotating streamwise vortices induced thermally by means of an imposed surface temperature gradient periodic in the spanwise direction *z*. It can be applied, for instance, to reduce separation losses on low-pressure turbine blades during their operation at low Reynolds numbers. The proposed technique is realized using electrically heated streamwise strips (e.g. in a form of high-resistance wires or a printed circuit board) regularly spaced along *z* which are flush-mounted in a thermally insulated material, thus creating the effect of thermal ribs or riblets.

Due to individual electric circuits used, surface properties (a distance between the activated strips and the temperature gradient) can be easily adjusted to current flow conditions during the operation. Accordingly, it will change the space-scale of the induced vortical structure and its intensity which was shown to be important to optimize the flow control, the imposed vortical space scale is recommended to follow the estimated theoretical values.

The "thermal ribs" can be switched on at necessary moments/regimes of motion providing the flexibility of the method beginning from the absence of any influence on the flow dynamics (no surface roughness of any kind, no temperature fields induced) to maximum influence depending on a design and material parameters. Separate heated sections can be used over the body surface with different parameters and independent electrical circuits which will provide the optimal boundary-layer control for a body with a complex geometry and varying regimes of operation.

Besides, a feed-back control system can be applied: measured varying flow parameters will automatically switch on an optimal heating regime of the thermal ribs and a necessary number of their sections over a body.

In addition to the active character and flexibility in operation, the essential feature of the proposed technique compared to mechanical ribs/riblets is a smooth surface that helps to avoid (1) additional skin friction because of the increased wetted surface, (2) limitations to flow direction variations (e.g. under body maneuvers) when an unfavorable orientation of a surface streaky structure can deteriorate the surface-flow interaction, (3) problems of the surface pollution, i.e. dealt with its cleaning and accounting for a spoilt configuration.

*PURPOSE*

The invention aims to provide an active, flexible and efficient technique and technologically reasonable device (economic and easy for manufacturing, reliable and simple in operation) for the beneficial influence on the near-wall flow structure yielding the reduction of drag, laminar-turbulent transition stabilization (delay), delay/prevention of the boundary-layer separation and/or heat transfer enhancement due to a specially arranged and easily controllable temperature distribution modeling a ribbed surface.

*BACKGROUND*

This approach is especially well justified for flows affected by body forces, such as flows under buoyancy (over heated surfaces) or centrifugal forces (over concave surfaces), where streamwise vortical structure manifests a universal feature of the vortex dynamics.

A method of thermally induced disturbances (merely through temperature dependent viscosity) was used in the context of perturbation studies of a boundary layer, described in [25, 28]. However the main idea and purpose of this research consisted in the elimination of disturbances in a boundary layer due to the formation of an out-of-phase velocity field. The laboratory experiments realized this idea in two stages. The first one represented the study of possibilities to induce controlled two- or three-dimensional velocity fields using heater arrays on a test surface. The second stage was to show the attenuation of this initial velocity field with a secondary one induced downstream in the same way using the heater array generating perturbations, which are temporally and spatially out of phase with the initial disturbance.

The work demonstrated effectiveness and reliability of the heater-array method to generate necessary velocity fields both in a laminar/transitional boundary layer, and in a viscous sublayer; the latter case considered the spanwise space-scale of induced disturbances of 90 wall units, thus defining the space resolution of the used heater-array.

However having demonstrated one tool for manipulations with the near-wall flow structure, the reported results are not directly applicable for the turbulent drag reduction and especially are not suitable for the boundary-layer separation control. Such applications should have been proceeded by the investigations and clear fundamental knowledge of the influence of local surface temperature gradients on the boundary layer structure depending on the space-scale and value of these gradients expressed in terms of the basic flow parameters with regard to a concrete application.

Thus the proposed advanced engineering solution of the boundary-layer control problem is based on the idea of simple and reliable generation and maintenance of longitudinal vortices with a scale dynamically correlated with the flow conditions; its practical realization is based on riblets/ribs as a starting design point.

*DESCRIPTION, MANNER AND PROCESS OF MAKING AND USING INVENTION*

The invention, as an engineering design, is grounded on the above-formulated idea to generate the beneficial vortical structure in a boundary layer under body forces. The solution is proposed in a form of the specially organized temperature field over a smooth surface. Improving the well-known solution in a form of mechanical riblets or ribs, i.e. surface inhomogeneity, they are modeled using temperature inhomogeneity over a smooth surface thus inducing thermally-driven flow inhomogeneities in the boundary-layer flow.

Heated flush-mounted strips oriented in the streamwise direction and separated from each other by thermally insulated strips create a temperature variation periodic in the spanwise direction, at the same time keeping the surface smooth. Thus imposing a surface temperature field, one can cause the development of a specially "designed" vortical structure in the boundary layer with given spatio-temporal characteristics correlated with the basic flow parameters (free-stream velocity $U_0$, surface curvature $R^{-1}$, and kinematic viscosity $\nu$) [32]:

$$L_0 = R\, Re_R^{-2/3}\,, \quad X_0 = A\, R\, Re_R^{-1/3}$$

$L_0$ is a minimal vortex space scale in normal and spanwise directions, $L_0 = 8\lambda_z$;
$X_0$ is a particular downstream distance (where the intensities of two available vorticity sources due to viscous and body forces become comparable resulting in the natural development of longitudinal vortices);
$Re_R$ is the Reynolds number based on radius ($Re_R = U_0 R/\nu$);
$A$ is a constant.

In its turn, a vortical flow structure in the near-wall region of a boundary layer is correlated with momentum and heat fluxes. Therefore flow manipulation with vortices induced, maintained and controlled by whatsoever means provide a possibility to control integral characteristics of the boundary layer such as skin friction or separation. The physical mechanism connecting the applied temperature field with the induced vorticity field was shown [55] to consist in the dependence of density and/or dynamic viscosity (and thus body- and/or friction forces) on temperature. It opens the prospects to apply the invention not only in flow conditions with the gravitation force accounted, e.g. like the configuration used in the water-channel experiments over the concave bottom section, but also in more general aerodynamic applications.

Having applied the invention idea to the low-pressure turbine blade, first of all, the $\lambda_{z0}$ scale of streamwise vortices naturally developing in its boundary layer was estimated [56]: it was found to be of a neutral type, i.e. neither amplifying, nor decaying in a downstream direction. Then according to the numerical results of [55], this value is to be used as a reference to choose the arrangement of the thermal "ribs" for optimal generation of longitudinal vortices to delay flow separation on a suction side of a turbine blade.

*HAS THE INVENTION BEEN TESTED?*

**1.**

The **experimental prototype** in a form of electrically heated longitudinal wires mounted on a flat Plexiglas and rubber-like walls of a water-channel test-section was fabricated and tested (N.F. Yurchenko, Hydromechanics Institute, Academy of Sciences, Kiev, Ukraine);
The method of thermal excitation of disturbances in a boundary layer and similar utilization of mechanical

vortex-generators, was used to study the possibilities of regular large-scale longitudinal vortices to control boundary layer integral characteristics. The experiments were carried out in a low-turbulence water-channel (Kiev, Ukraine) over flat and concave surfaces [46-48, 52] and in a wind-tunnel equipped for heat transfer measurements (Kaunas, Lithuania) [49, 51, 54]. The experiments aimed

1) to demonstrate an effect of thermally induced disturbances/longitudinal vortices;
2) to investigate the boundary layer receptivity to the scale, $\lambda_g$, of induced vortices;
3) to give preliminary assessments for the numerical simulation.

(See the Report above)

**2.**
**Numerical model** was developed and tested for the simulation of the boundary-layer vortex dynamics affected by the thermal ribs in correlation with the experimental formulation of the problem and the experimental data mentioned above (J.W. Delfs, DLR, Braunschweig, Germany).
Calculations of the basic parameters have given an insight into the mechanism of the boundary-layer vortex dynamics affected by the thermal ribs, demonstrated the evolution of the induced vortical structure and provided quantitative grounds for practical applications in a form of recommendations to optimal generation and maintenance of the beneficial flow structure in a boundary layer.

(See the Report above)

**3.** The boundary layer structure was examined over a low-pressure turbine blade (R.Rivir, N.Yurchenko, Turbine Branch, Turbine Engine Division, Aero Propulsion and Power Directorate, Wright Laboratory, WPAFB, USA) taking into account centrifugal effects; the information was used to develop recommendations related to the generation and maintenance of a vortical flow structure which is optimal from the viewpoint of hydraulic losses, especially because of the early boundary layer separation.

The method was proposed to delay flow separation on a suction side of a turbine blade using thermal ribs which will stimulate the development of streamwise vortices. In this connection, the model of a low-pressure turbine blade was fabricated with flush-mounted electrically heated streamwise wires for tests in a wind tunnel. Preliminary visualization of the boundary layer using the liquid-crystal coating showed the favorable effect of the heated ribs: the separation zone moved downstream compared to the undisturbed case.

*ADVANTAGES AND NEW FEATURES*

The advantages of the **THERMAL RIBS** compared to the prototype mechanical riblets consist in the following:

1. smooth surface, i.e. no additional friction because of the increased "wetted" surface and no limitations to flow direction variations (body maneuvers) when the orientation of a surface streaky structure is important;
2. invariant "geometry" not depending on the surface pollution;
3. basic space-scale of generated vortical structure $\lambda_g$ is to be chosen from the estimated $L_0$ value depending on the defining flow parameters (free-stream velocity, viscosity, surface curvature, flow temperature);
4. active method of a boundary-layer control: easy dynamic regulation of the vortical system intensity due to the variation of a temperature gradient between the adjacent strips -- from $\Delta T = 0$ when the ribs are not needed to $\Delta T_{max}$ corresponding to critical flow conditions/motion regime;
5. regulation of an induced spanwise flow scale $\lambda_z$, due to the amount of heated strips that varies the distance between adjacent activated thermal ribs depending on the motion requirements: independent electrical circuits can switch into operation every heated strip, every second, third, fourth one, etc. satisfying the condition of $\lambda_z = n\lambda_{gmin} = nL_0$;
6. sectioning of the ribs distributed over the surface with individual parameters of the sections (space scale, temperature gradient $\Delta T$, orientation along a body) controlled by independent electrical systems;
7. possibility of the feed-back management: measured varying flow parameters (e.g. shear stress or fluctuating velocities) can automatically switch into operation a necessary number of sections and optimal heating regime of thermal ribs.

*ALTERNATIVE MODES OF THE INVENTION*

Low-pressure turbine blades are typically smooth, designed for attached, non-separated flows. Attempts to increase the aerodynamic loading on the blade to minimize or reduce the weight results in separation at low Reynolds numbers. In its turn, it results in the turbine efficiency loss of 1-6% (Allison Chart 1998, Sharma CFD 1997) and a proportional increase in specific fuel consumption at cruise at high altitude.
Thus the invention can be practically useful for the optimization of a low-pressure turbine performance and operation at low Reynolds numbers.

More generally, the invention can be applied for any bodies of complex configuration affected by body forces. It can be applied for the flow control over any concave and convex surfaces given (locally) appropriate centrifugal force conditions, e.g. due to blowing through a two-dimensional slot in the surface. Besides, the applications are not restricted by certain fluids, i.e. the thermal ribs work both in air and in water or in oil, and by a nature of a body force (centrifugal forces, buoyancy or electromagnetic forces in special cases of electro-conducting fluids).

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